How Safe is Safe?
Dam Safety from the Viewpoint of Downstream Communities.

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Abstract

Reservoirs and dams are often situated in the mountains upstream of cities and towns. This implies a theoretical but difficult to evaluate hazard potential for downstream communities. This paper reflects experiences of the related safety analysis practice including the steps from the breach estimation towards the drawing of special hazard maps.

Introduction

Vulnerability and resilience of communities against floods have changed during the centuries. During the last 100 years upstream of many cities reservoirs for water supply or hydropower have been erected that must be included when considering the development of vulnerability and resilience of towns and cities downstream.
In Germany Owners and Operators of installations and plants with a high hazard potential are due to inform the authorities about possible consequences of an accident. This will help to detect hazards and to take measures if necessary. For operators of reservoirs and dams this means to inform the authorities or public with the help of inundation maps not only about the consequences of natural floods but also about the flooding in the improbable case of a dam failure.
Although it has often been claimed that our dams are safe „in all probabilities“ we must recognize that some medium sized German dams (6 m < height < 15 m) as e.g. Kirchheim 1977, Gissigheim 1984, Glashütte 2002 and Witka 2010 (site in Poland with consequences in Germany) and many small dams and levees failed during the last decades.
From these incidents can be derived, that residual risks do exist and all necessary steps must be taken to detect them and to describe their possible impact and extent.
Appropriate Investigations have to be understood by the sensitive public as efforts to assess the dam safety and not as an evidence of insecurity of the dams.

Breach Scenarios

Breach scenarios have been investigated by means of scientific case studies for a long time. Nevertheless there are many questions still open in this field, especially concerning the time-depending breach development being different for different dam types. This is why often statistical records of observed failures are used to estimate the possible failure mode. When embankment dams failed in the past this mostly happened due to overtopping or piping with subsequent retrogressive erosion during 0.5 to 4 hours. Often this produced a trapezoid or almost rectangular breach which released the water as over a broad-crested weir. That geotechnical erosion breach models allow only a very coarse estimation (e.g. dQ = 50% for Tous dam, Spain) can be seen from the wide spreading results in space and time. Masonry and concrete dams can fail within only a few minutes due to unsufficient safety against sliding or overturning or the failure of abutments (arch dams).
After the 9-11-2001 the willful destruction of dams came into the focus of attention. In this

case the breach could have the above described or the shape of a semicircle especially at concrete or masonry dams.
For the evaluation of possible failures often fault or event trees are used respectively.
Figure 1 shows the outflow from a combined embankment and concrete dam, for which failure modes were derived from the stability analysis and the incident design flood hydrographs. The significant stability problems arose from the design earthquake. At least in this case study can be observed from the distribution of the yearly highest natural peak discharges versus the recurrence period that comparable discharge values have similar exceedence probabilities in the range of design discharges (Figure 1).

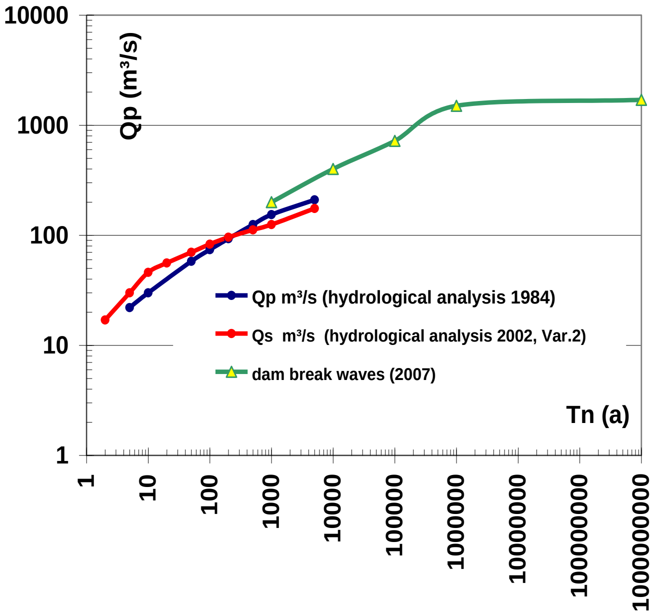

Figure 1: peak discharges vs. recurrence intervals for a case study with natural floods (two left curves from two studies) and dam failure (right curve)

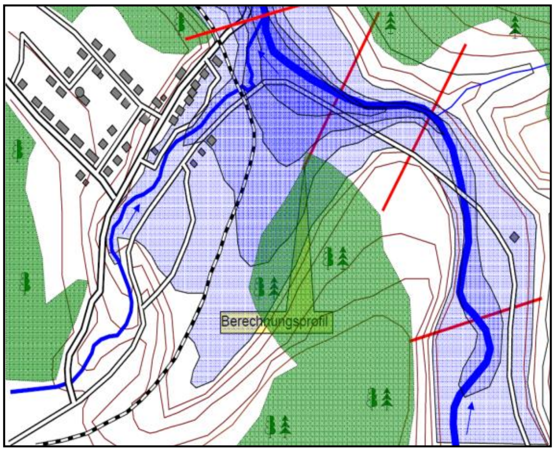

Figure 2: special hazard map with inundation area (and depth) due to a dam break wave

Reservoir Outflow through a Breach

When failing, dams will release a two phase flow. In particular at embankment dams breaching during a flood, the volume of transported solids (bedload) can have the magnitude of the escaping amount of water. The research activities in this field have been increased during the last years. But the common practice mostly models outflow on fixed beds.
Outflow and reservoir level can be calculated depending on the nonsteady discharge due to the transient breach development.
While in the case of gradually increasing breach the flow rate can be calculated according to the broad crested weir. The sudden opening of a concrete or masonry dam can be described by means of the solution by *Ritter* having been validated experimentally on principle during the last 100 years. This yields an initial water level at the site of a little bit less than the half of the water depth ($4/9 \cdot H$) before the breach. The outflow remains approximately constant until the negative surge has passed the reservoir.

Downstream Surge

Dam break waves propagate more rapidly than natural flood waves in the downstream vicinity of the failed barrage (5 – 70 km/h) and exceed their depth considerably. For the hazard

estimation the water depth, the flow velocity, the height of the surge as well as the concentration and quality of the moving bedload and floating matter are important.
For the analytical description of the wave propagation mostly the Saint-Venant-Equations are used, which combine the dependent variables discharge and water level with the independent variables place and time.
For the practical computation several one- and two-dimensional hydro-numerical programs are available. Reliable results are yielded from those programs that keep numerical stability also with high discharge and water level gradients (e.g. MIKE 11, 21 [DHI-DK], HYDRO_AS-2D [D], DAMBRK [USA], EDF [F], ENEL [I] u.a.). As taking in account the momentum exchange with the water in the floodplains and the subsequent losses two-dimensional programs tend to yield slower wave fronts. Therefore at one-dimensional models a reduced roughness-value (Strickler, or a higher Manning-value) should be used.
Molinaro [4] suggests a mean roughness of 15 $m^{1/3}/s$ for narrow gorges an settlements. This value should be verified by sensitivity tests (e. g. k_{St} = 10 $m^{1/3}/s$ to 20 $m^{1/3}/s$, because the roughness is one of the influencing variables with the highest uncertainty concerning the calculated water level. Further uncertainties can arise from the estimated breach outflow hydrograph and the spatial resolution in the digital terrain model.
The comparison of calculations with 1-D and 2-D models and steady/unsteady flow have shown, that even with a certain smoothing and generalization of the digital terrain model practicable results can be yielded and the precision depends on the constraints and the initial conditions.
In inundated urban areas decisions concerning the definition of the flow cross section area have to be made. If the flow velocity and distribution in every street is needed 2-D calculations with a high solution of the net must be used with every house (which will remain in place) as a not wetted area (dry cells). If only the water level is needed as a result 2-D models with less resolution and in the case of obvious or known flow path also 1-D models can be used with appropriate lower (rougher) *Strickler* values. Figure 3 shows the comparison of different calculation methods for a case study.

Results

The objective of the investigation of dam break waves is the drawing up of hydraulic profiles with water depth, water level, discharge, flow velocity and arrival time of the wave front as well as inundation maps with these information (Figure 2) for emergency plans, the hazard estimation, insurance purposes and the inundation danger of important structures like a chemicals factory or a nuclear power plant. These event or hazard maps are obtained by finding the intersection lines between the calculated water level and the terrain model.
If due to an one-dimensional calculation at each flow cross section only a mean velocity is available the velocity distribution can be estimated by means of known isovel patterns taking into account the principle of continuity.
Using two-dimensional models a direct plotting of the inundated area is possible. Further the flow velocities can be displayed in colors or with vector arrows. At important spots or flow sections of the maps often the arrival time of the wave front, the maximum water depth and the maximum velocities are shown. If in these special hazard maps zones of different hazard shall be displayed this is mostly done by using the intensity (e. g. water depth x flow velocity; sediment layer thickness) and the occurrence probability. A flood event with high intensity that is expected frequently represents a high hazard and a high risk. Due to its very small occurrence probability a dam break often represents only a medium or small risk although it possesses a high intensity. This applies when risk is defined as a product of probability and consequences. Often the consequences are expressed by the monetary damage loss. But in addition also fatalities and destroyed parts of the cultural heritage as well as further aspects

play an important role. To quantify and compare the hazard to the people e.g. the expression V*H*I*EW/L can be used with the symbols explained in Figure 4.

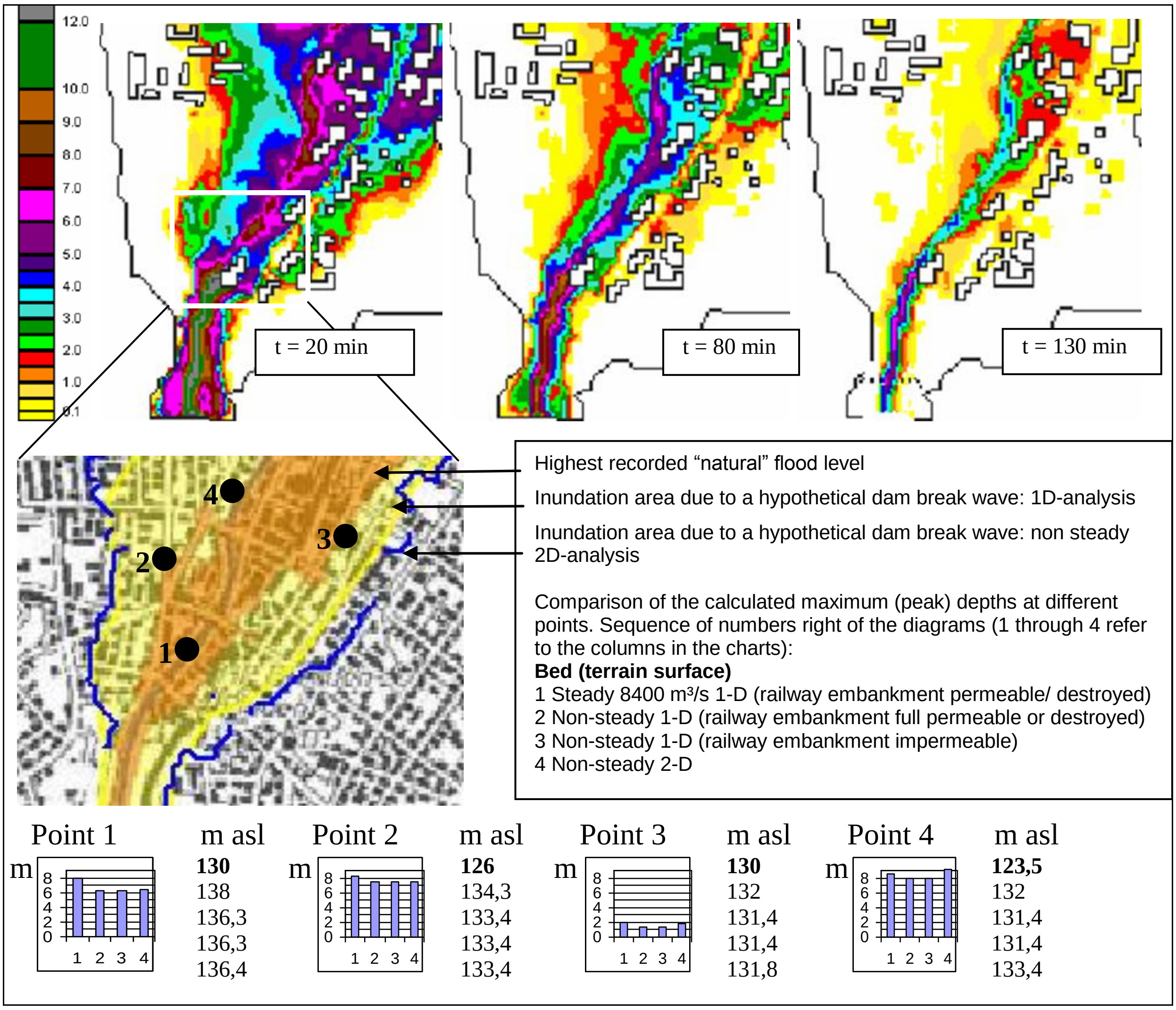

Figure 3: comparison of flood propagation results using one- and two-dimensional hydronumerical programs: top: water depths during the propagation of a dam break wave (the white areas indicate large buildings which are assumed to remain in place during the surge); left: maximum inundation area and water depth during the event (detail)

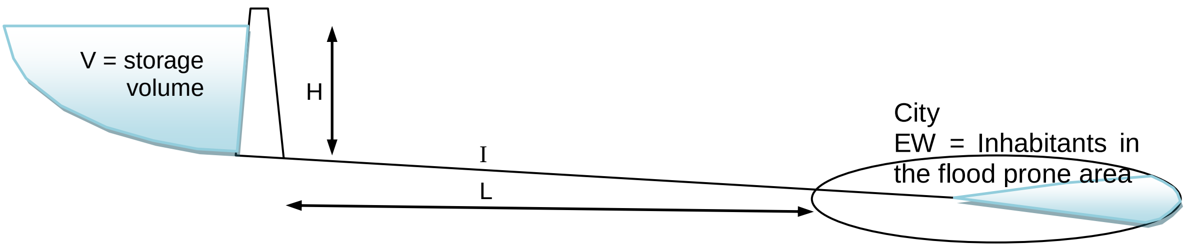

Figure 4: Sketch for risk number

The produced special hazard maps should be provided in well usable form: as conventional hardcopy on paper (to make it avaiable also in the case of blackout of electricity, communication and data networks) but also in electronically stored form (GIS, internet download with possibly only authorized access). Figure 3 shows the comparison of the inundation area for an urban area due to the highest known natural flood and a dam break some 20 km upstream. In addition different points in time of the non-steady process as well as the results of different approaches have been displayed.

Conclusions

Much is done to keep our dams safe: high level standards and guidelines, best practice, close mashed supervision and highly qualified dam operation personnel.
The same we had also assumed to be valid for nuclear power plants that would affect much more people (even with long-term consequences) than dams in the case of failure. But the case in Fokushima, Japan, with loads beyond the design earthquake and Tsunami loads have shown us that the empirical failure probability of nuclear power stations is much higher than originally calculated and expected by the *Association for Nuclear Safety*. The empirical failure probability for all nuclear power plants by *Kauermann & Küchenhoff* [11] would be some 1: 6666 per year [assuming the same failure probability for all plants, also if of different type; 2 accidents/ 30 years/442 existing nuclear power plants (during the whole 30 years)].
If the same simplified calculation is made with 4 failures of medium sized German dams during the last 40 years a failure probability of 1:9000 per year ($1,11*10^{-4}$) for a medium sized dam is yielded. This is less frequent (more secure) than for nuclear power plants (s. above)! In particular due to the lower number of fatalities at the reported dam breaks the Risk = P * C at failing dams is far more than one magnitude less than at nuclear power plants. In this first approach the number of the not registered German medium dams was estimated to be about 3 times the number of dams registered by ICOLD.
For the about 300 registered large German dams (no failure during the last 40 years) the probability of about 1:14000 ($0.71*10^{-4}$) has been received which is more than one magnitude less (more unsecure) than the usually calculated results. For this calculation the upper limit of the confidence interval by using the X^2 -function was inserted.
Otway and Erdman [7] presented limiting values for the acceptance of risks: a probability of 10^{-3} per year with one fatality requires immediate measures of risk reducing, 10^{-4} demands medium-term measures, 10^{-5} would initiate warnings and at 10^{-6} individuals do not feel concerned.
We can see that the results of the above approximation lie in the medium range of the probabilities at about 10^{-4} and absolutely justify medium-term risk reducing and precautionary measures like drawing up and providing hazard maps.

The possible consequences should be known to enable the responsible authorities and forces to prepare appropriate preventive measures like the installation of early warning systems or the elaboration of emergency plans.
The international legislation and guidelines differ considerably concerning the handling of dam break hazard maps and related emergency plans. In the frame of the residual risk assessment at dams the investigations should include the breach development, the outflow hydrograph, the surge propagation and its consequences. The result of the investigation is normally a special hazard map that should be available at least at the dam owners, operators and competent (disaster control) authorities. It can be of advantage if also the concerned people are informed.

As many of the input data are uncertain quantities the hazard map displays a certain failure

szenario. Different constraints and initial conditions can be taken into account by elaborating several maps. Another way for future dam break wave calculations could be the application of statistical methods that would produce water levels with a certain exceedence probability.
The legal claim for providing information concerning the possible hazard release is construed by the dam owners and operators in a different way. Especially on the question if the documents have to be ready or can be made only on demand different answers are given. Also the question if the *Directive 2007/60/EC on the assessment and management of flood risks* includes these „artificial“ is discussed occasionally.

It seems to the author of this paper that among the owners and operators four perspectives can be detected: The first have published the results of the hypothetical dam break. The second have these information available but prefer not to publish them to avoid misunderstandings. The third plan to cope with the problem only after request by the authorities and the fourth are not aware of any risk related to their installations. A first estimation for large dam operators in Germany might come to the percentages of 1%, 30%, 40% and 29% where the classement into group 3 and 4 respectively is difficult and may vary.

In the author’s opinion despite the very low dam failure probability provisional measures should be taken as it is usual also for natural floods that are mostly lower but with a higher probability. Especially for dams upstream of urban areas these could include the drawing up of appropriate documents with hazard maps by the dam operators.
Furthermore the disaster control authorities should look after and deal with these documents and develop them towards emergency plans. Also in this field still some work has to be done.

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